06-Solar Resource Part 1

ECEGR 452

Renewable Energy Systems

Overview

- Solar Characteristics
- Extraterrestrial Solar Irradiance
- Angle of Incidence
- Solar Irradiance

Introduction

- Most renewable energy systems convert energy whose source is ultimately the sun
  - 3.8 YJ (1 x 10^{24})/yr pass through the atmosphere
  - approx. 10,000 the amount of energy used by fossil fuels and nuclear per year
- In this lecture we investigate the nature of solar energy

Solar Characteristics

- Solar energy originates from the sun
- Driven by nuclear fusion of hydrogen into helium
- Surface temperature approximately 5500^{o}C

Solar Characteristics

- Heat is transferred from the sun to the Earth via electromagnetic radiation
  - also called solar radiation
- Nature of the electromagnetic radiation is a function of the temperature and emissivity

Solar Characteristics

- Solar radiation from a blackbody (the sun can be approximated by a blackbody) is related to temperature from the Stefan-Boltzmann Law

$$G = \sigma T^4$$

- where
  - G: irradiance or solar irradiance (W/m^2)
  - σ: Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ J/(sm^2K^4)

Example

- Calculate the irradiance of the sun (approximate as a blackbody at a temperature of 5500^{o}C) at its surface

$$G = \sigma T^4$$

$$\sigma = 5.67 \times 10^{-8} \text{ J/(sm}^2\text{K}^4\text{)}$$

Example

- Calculate the irradiance of the sun (approximate as a blackbody at a temperature of 5500°C) at its surface

$$G = \sigma T^4$$

$$\sigma = 5.67 \times 10^{-8}\ \text{J/(sm}^2\text{K}^4\text{)}$$

$$G = \left(5.67 \times 10^{-8}\right)\left(5500 + 273\right)^4 = 6.3 \times 10^7\ {}^{W}\!/\!_{m^2}$$

- If the sun was the temperature of a candle it would be:

$$G = \left(5.67 \times 10^{-8}\right)\left(1000 + 273\right)^4 = 1.50 \times 10^5\ {}^{W}\!/\!_{m^2}$$

Solar Irradiance

- Units of G (W/m^2) are power density
- Integrate G over time to find irradiation, energy density (J/m^2 or kwh/m^2)
- Insolation (not insulation): irradiation whose source is the sun

Extraterrestrial Irradiance

- What is the irradiance that arrives at the top of Earth’s atmosphere (extraterrestrial)?
- Irradiance will decrease as the distance from the sun increases
  - decrease in proportion to the square of the distance

Extraterrestrial Irradiance

- Irradiance at the sun
  - $G_{sun} = 6.3 \times 10^7 \ W/m^2$
- Surface area of a sphere $A = 4\pi r^2$
  - r: radius of the sphere (m)
- Radius of the sun: $R_{sun} = 695{,}000$ km
- G at any distance R from the sun is:

$$G = G_{sun}\left(\frac{4\pi R_{sun}^2}{4\pi R^2}\right) = G_{sun}\left(\frac{R_{sun}^2}{R^2}\right)$$

↑

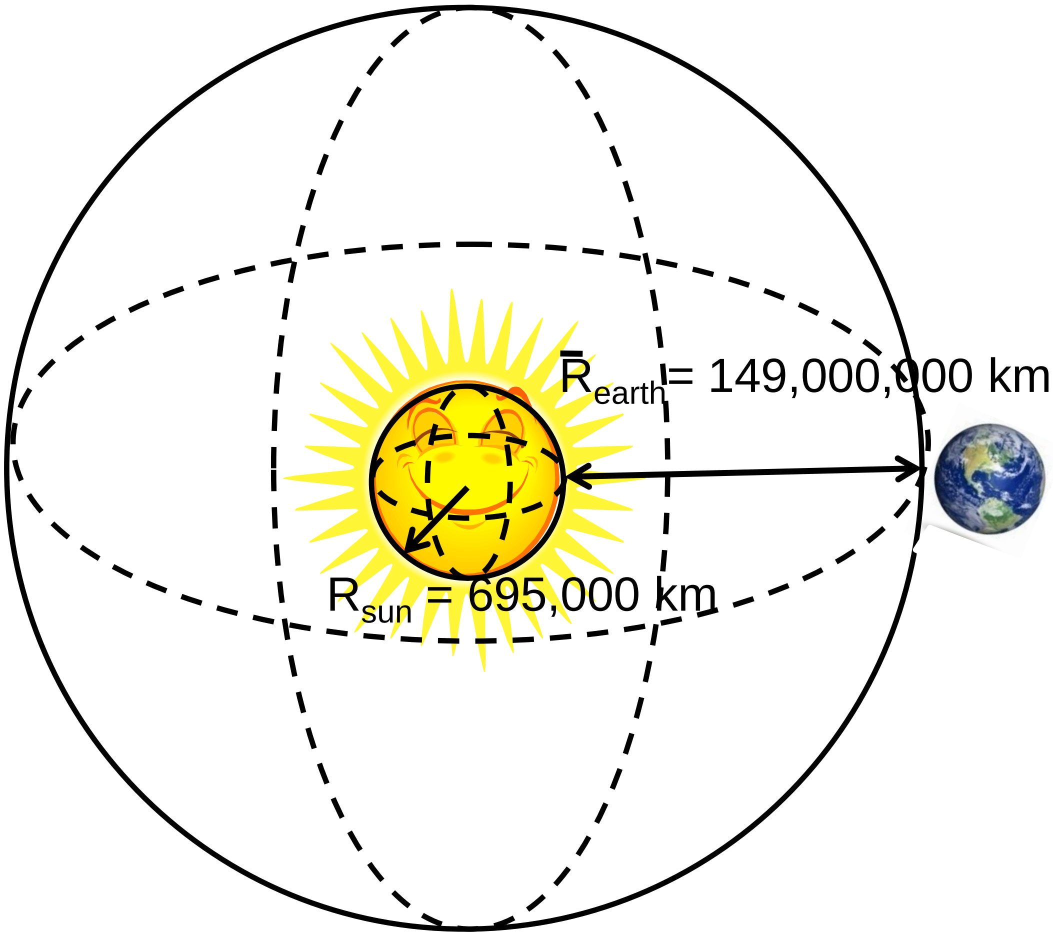
Ratio of surface areas

Extraterrestrial Irradiance

- What is the extraterrestrial irradiance at the Earth?
- Average distance from Earth to sun:
  - $\bar{R}_{earth}$ = 149,000,000 km
- Solving:

$$G = G_{sun}\left(\frac{4\pi R_{sun}^2}{4\pi \bar{R}_{earth}^2}\right) = 1370 \text{ W/m}^2$$

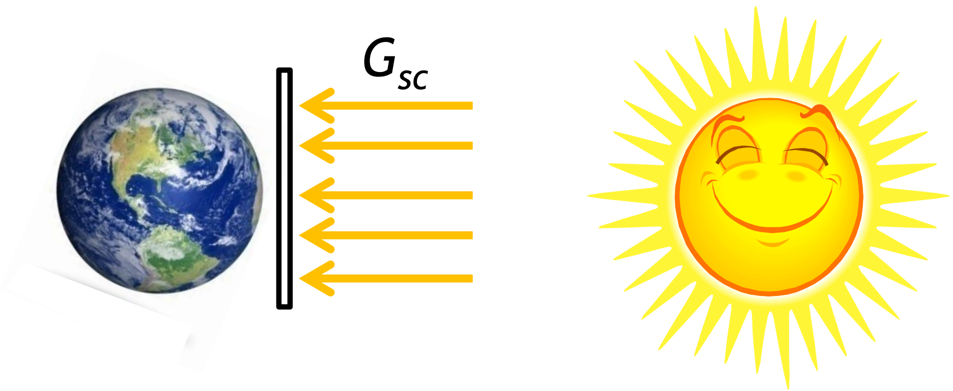
Extraterrestrial Irradiance



*not to scale

Solar Irradiance

- The accepted average solar irradiance value for the top of the Earth's atmosphere (extraterrestrial) is 1367 W/m^2
  - based on satellite data
  - plane normal to the sun
  - G_{sc} = 1367 W/m^2 defined as a *Solar Constant*



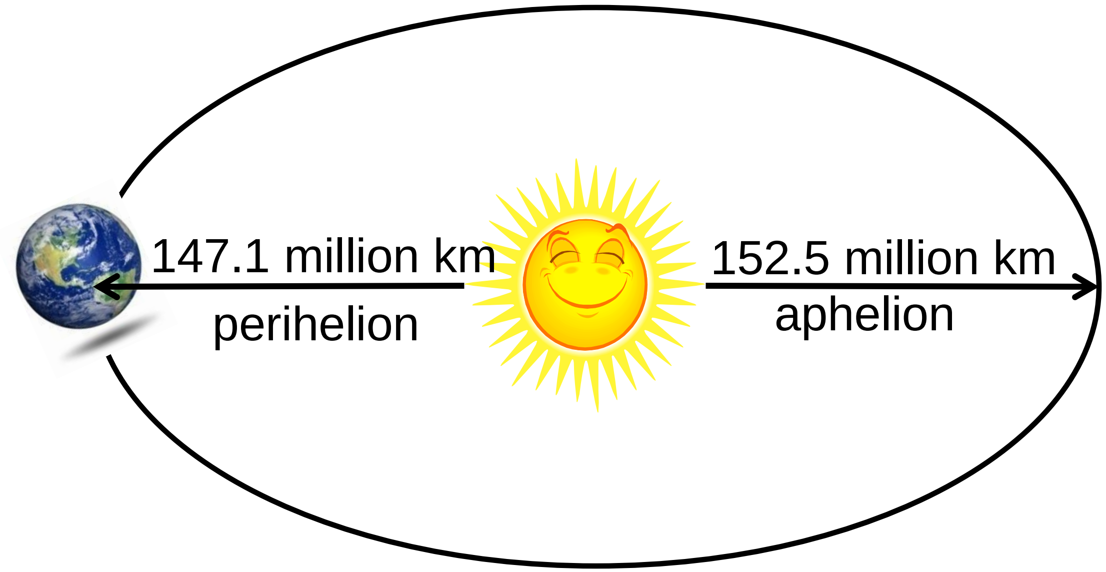
Solar Astronomy

- G_0: extraterrestrial irradiance on horizontal surface (W/m^2)
- G_{0n}: extraterrestrial irradiance on a plane normal to the radiation
- G_{0T}: total extraterrestrial irradiance on a surface, accounting for surface tilt, if any (W/m^2)
- Subscript 0 means extraterrestrial (top of the atmosphere)

See Lecture 0X-Solar Nomenclature

Extraterrestrial Irradiance

- Earth's orbit is nearly circular
  - a "tilted" view is shown



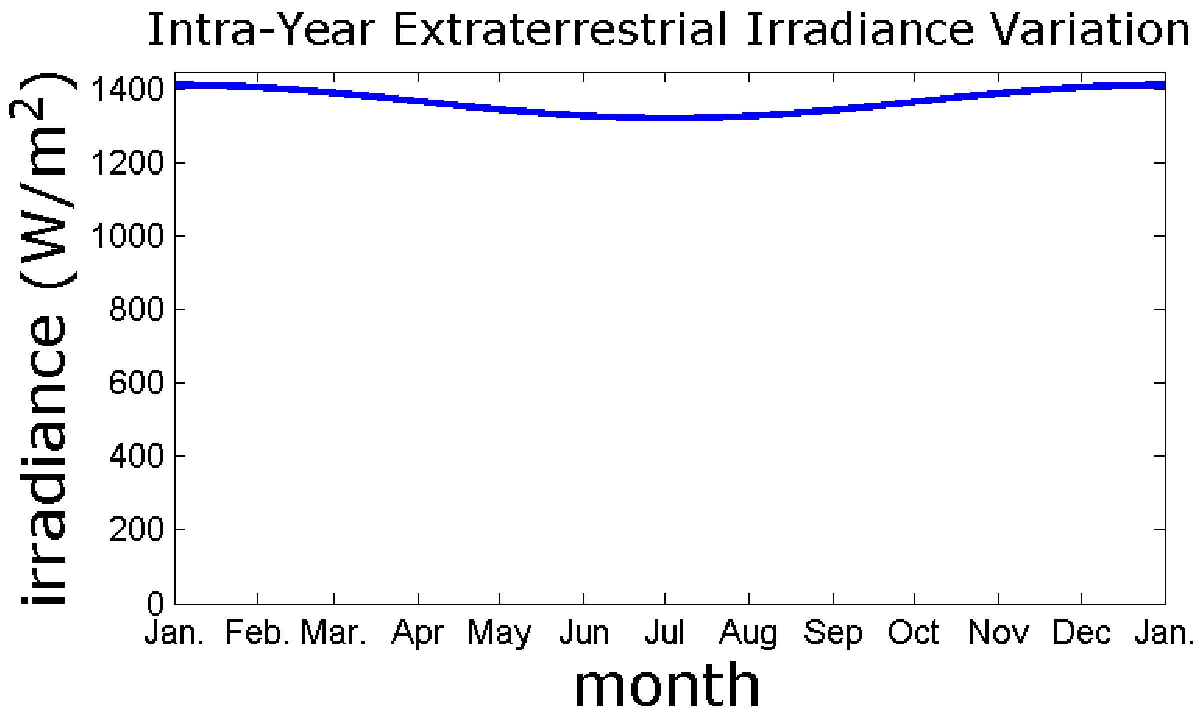
Astronomy Trivia

- What day of the year is the Earth closest to the Sun (perihelion)?
  A. December 21st
  B. June 21st
  C. September 21st
  D. March 21st
  E. January 4th
  F. June 4th
  G. October 18th

Astronomy Trivia

- What day of the year is the Earth closest to the Sun (perihelion)?
  A. December 21st
  B. June 21st
  C. September 21st
  D. March 21st
  E. January 4th
  F. June 4th
  G. October 18th
- Seasons have nothing to do with the distance from the sun

Extraterrestrial Irradiance



Extraterrestrial Irradiance

- We can account for the distance from the sun:

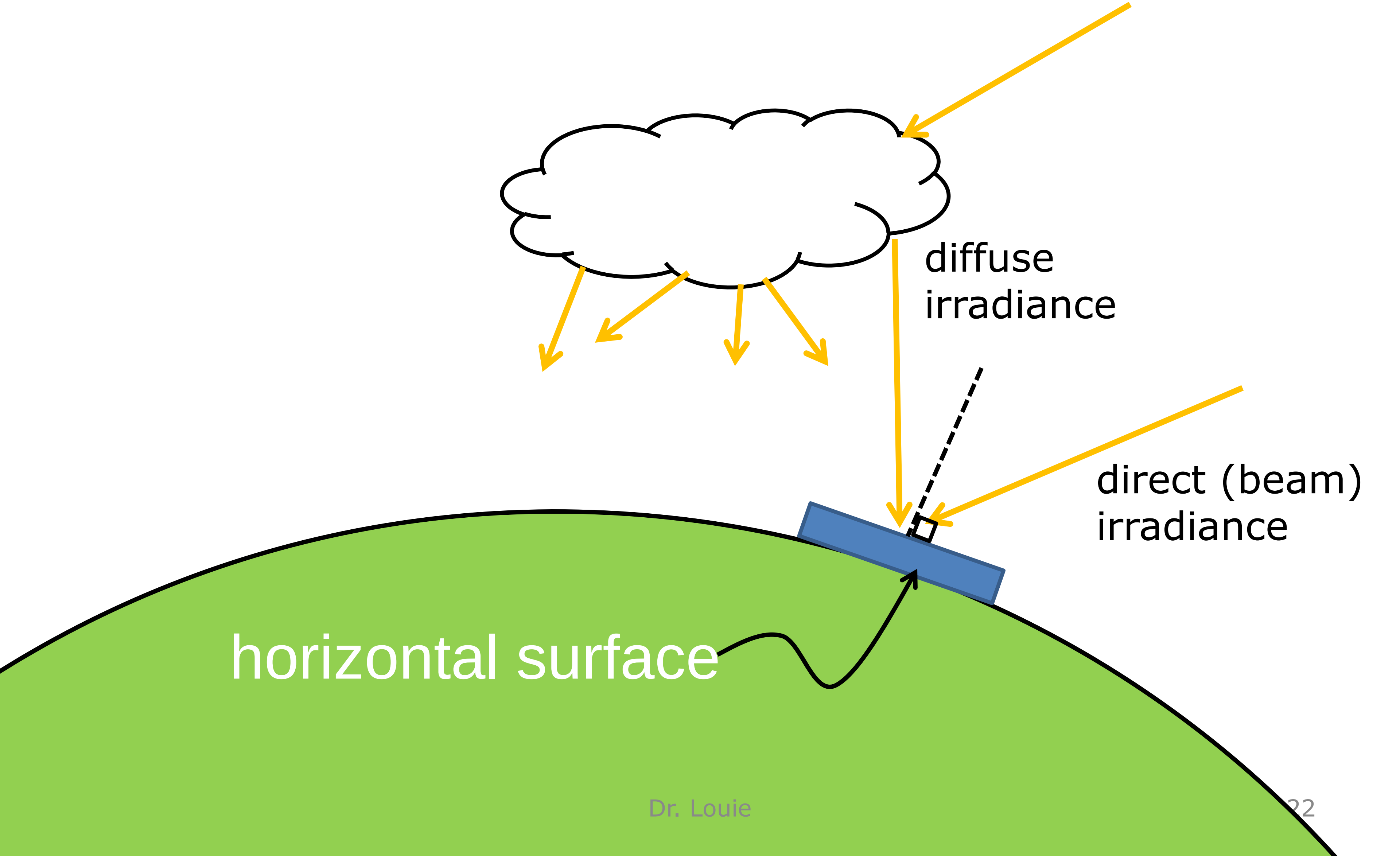
$$G_{on}(d) = G_{sc}\left[1 + 0.033\cos\left(2\pi\left(\frac{d}{365}\right)\right)\right]$$

  - *d* is the day of year (*d* = 1 on January 1)
- This is an approximate equation
- Peak-to-peak variation is small (<7%)

Solar Irradiance

- Design of solar renewable energy systems requires knowing:
  - Irradiance, insolation
  - Direction
  - Diffuse or direct
- We want to be able to quantify the nature of the solar irradiance on a given surface on the Earth
- First consider horizontal surfaces

Solar Irradiance



Solar Irradiance

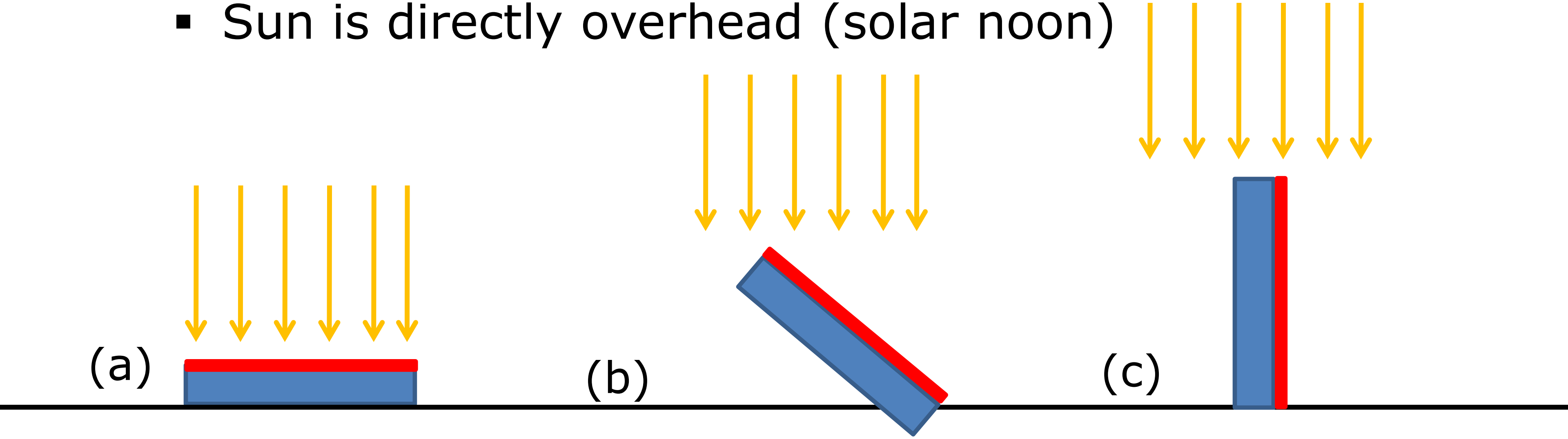
- Direct (beam) irradiance: solar irradiance received from the sun directly. It has not been scattered by the atmosphere.
  - Subscript b is used
- Diffuse irradiance: solar irradiance received from the sun after it has been scattered by the atmosphere
  - Implies change in direction
  - Subscript d is used
- Unless specified elsewhere, assume G_b and G_d are referenced to a horizontal surface

Solar Irradiance

- Global irradiance: sum of beam and diffuse irradiance
  - $G_{GHI} = G_b + G_d$
- Global Horizontal Irradiance (GHI): global irradiance on a horizontal surface
- GHI is a commonly measured quantity, from which G_b and G_d are estimated

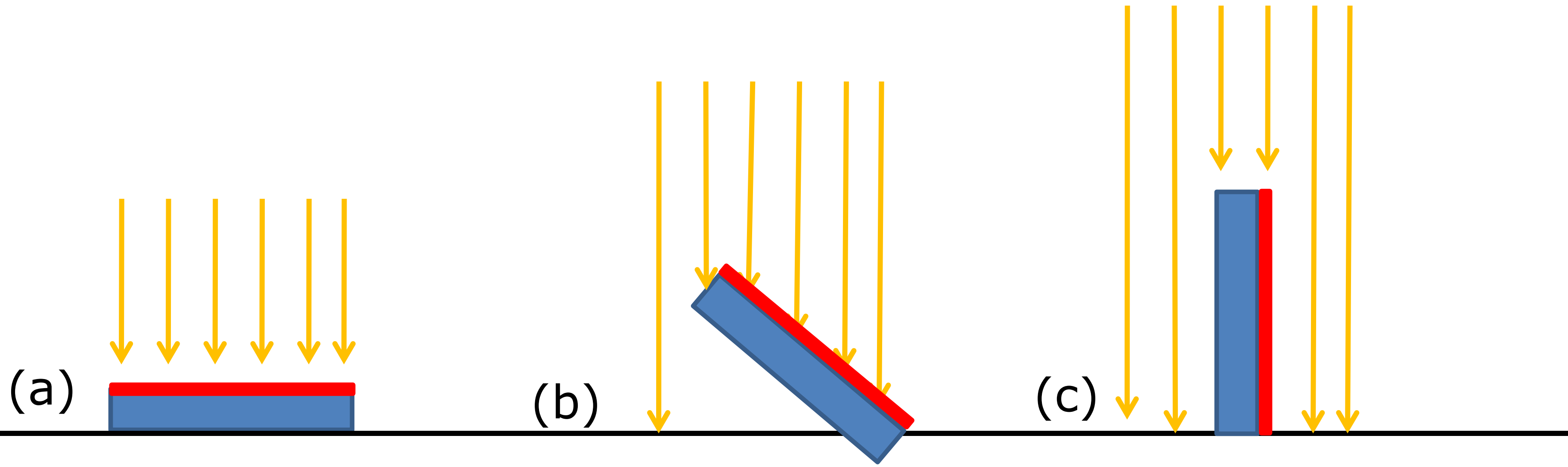
Accounting for Angle of Incidence

- Which surface receives the most irradiance, G?
- Assume:
  - No atmosphere, no ground reflectance
  - Only irradiance on the face counts
  - Sun is directly overhead (solar noon)



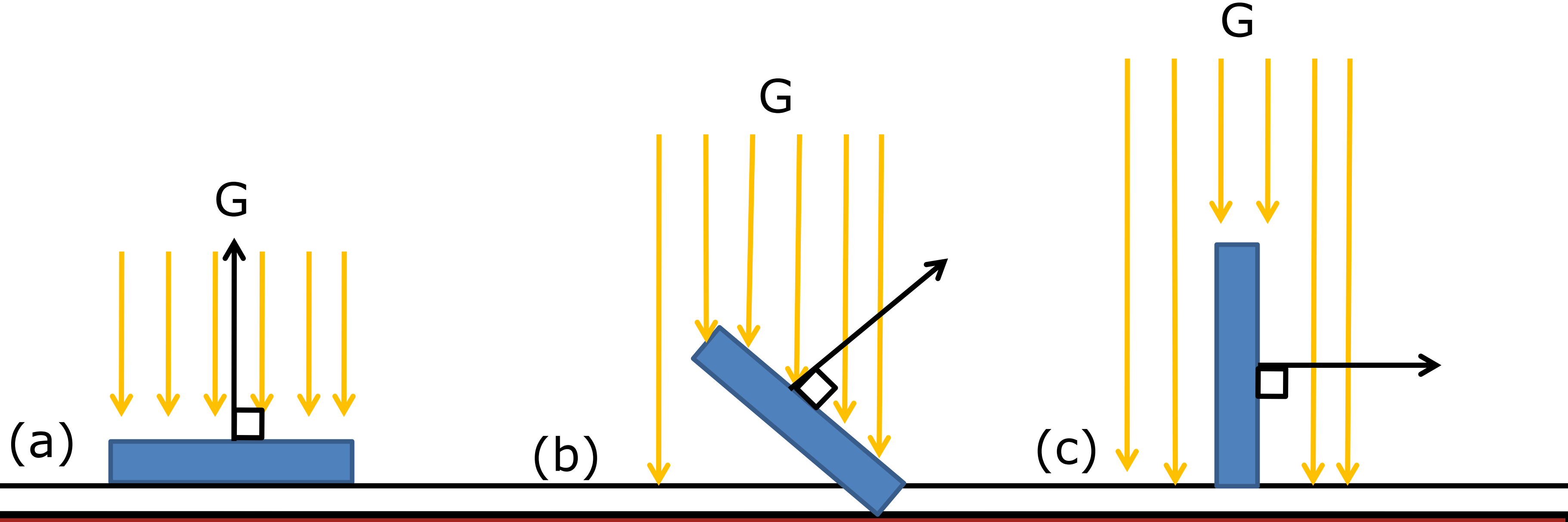
Accounting for Angle of Incidence

- Surface (a): receives all irradiance
- Surface (b): receives a portion of the irradiance
- Surface (c): receives no irradiance



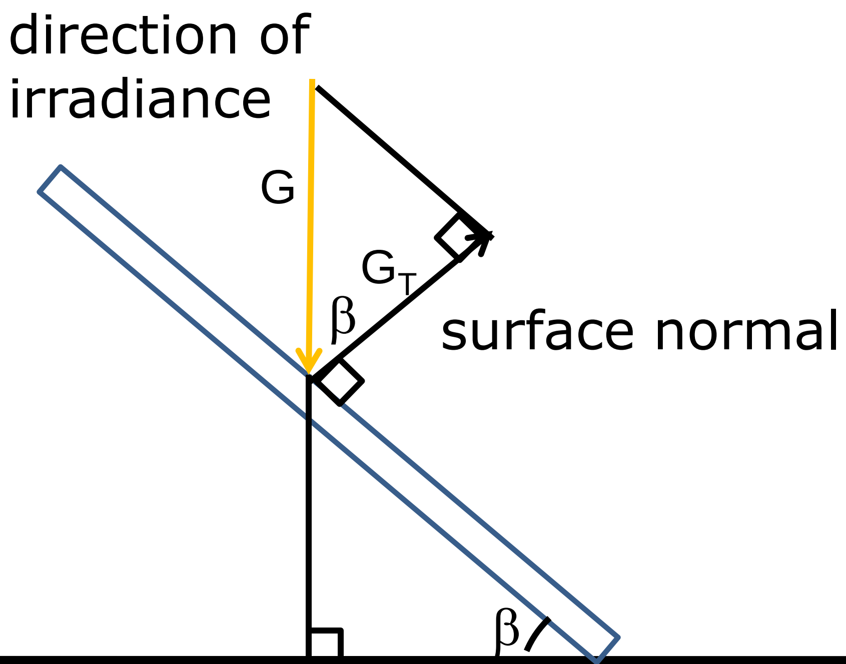
Accounting for Angle of Incidence

- Compute the projection of G onto the normal of the surface
- θ: angle of incidence, degrees
- G_T: total irradiance received on a surface, accounting for tilt, if any (W/m^2)



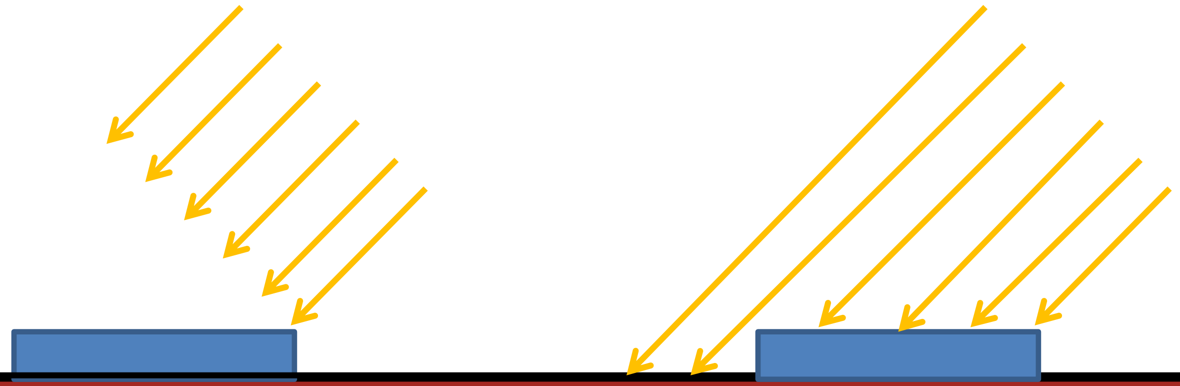
Accounting for Angle of Incidence

- Let β: tilt of the surface, degrees
- Under assumptions given $\theta = \beta$
  - $G_T = G\cos(\theta)$



Accounting for Angle of Incidence

- Similar derivation if the surface is horizontal, but the irradiance is at an angle



Accounting for Angle of Incidence

- The angle between the sun and a horizontal surface is the zenith angle, θ_z
- VERY IMPORTANT!!!
- Zenith angle is the angle of incidence for a horizontal surface (special case)

Accounting for Angle of Incidence

- Top of the atmosphere irradiance for horizontal surfaces:
  - $G_0 = G_{0n}\cos(\theta_z)$

- Accounting for surface tilt, if any:
  - $G_{0T} = G_{0n}\cos(\theta)$

Accounting for Angle of Incidence

- Compute the extraterrestrial irradiance on a horizontal surface on October 18 when the Zenith angle is 60^o, accounting for intra-year irradiance variability. [hint: October 18 is the 291st day of the year]

Accounting for Angle of Incidence

- Compute the extraterrestrial irradiance on a surface on October 18 when the Zenith angle is 60°.
  - $G_0 = G_{0n}\cos(\theta_z)$

$$G_{on}(d) = G_{sc}\left[1 + 0.033\cos\left(2\pi\left(\frac{291}{365}\right)\right)\right] = 1380$$

$$G_0 = 1380\cos(60) = 690 \text{ W/m}^2$$

Accounting for Angle of Incidence

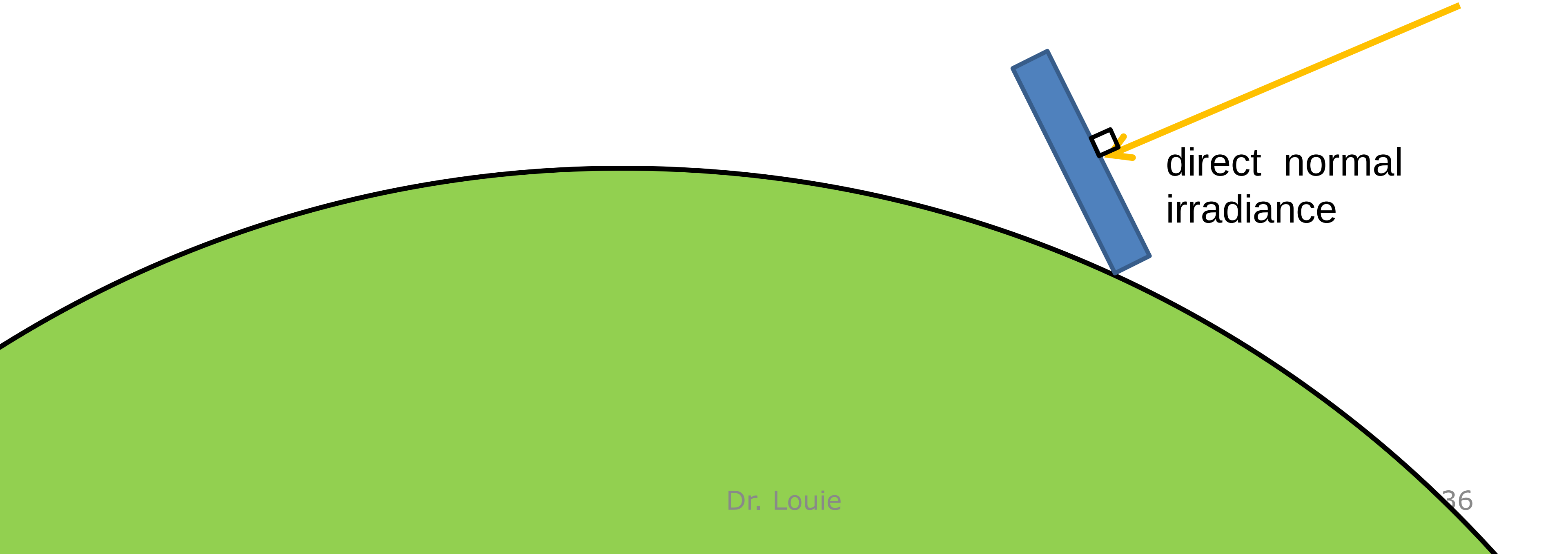
- Angle of incidence is implicitly accounted for when GHI is measured
  - G_b and G_d must also account for angle of incidence

Solar Irradiance

- Concentrating Solar Power (CSP) systems can only utilize beam irradiance
- CSP receivers also track the sun to maximize energy
  - Receiver face stays normal to the sun for most hours
  - Direct Normal Irradiance (DNI): beam irradiance received by a surface normal to the irradiance (G_{DNI})
- Possible (but cumbersome) to estimate DNI from GHI

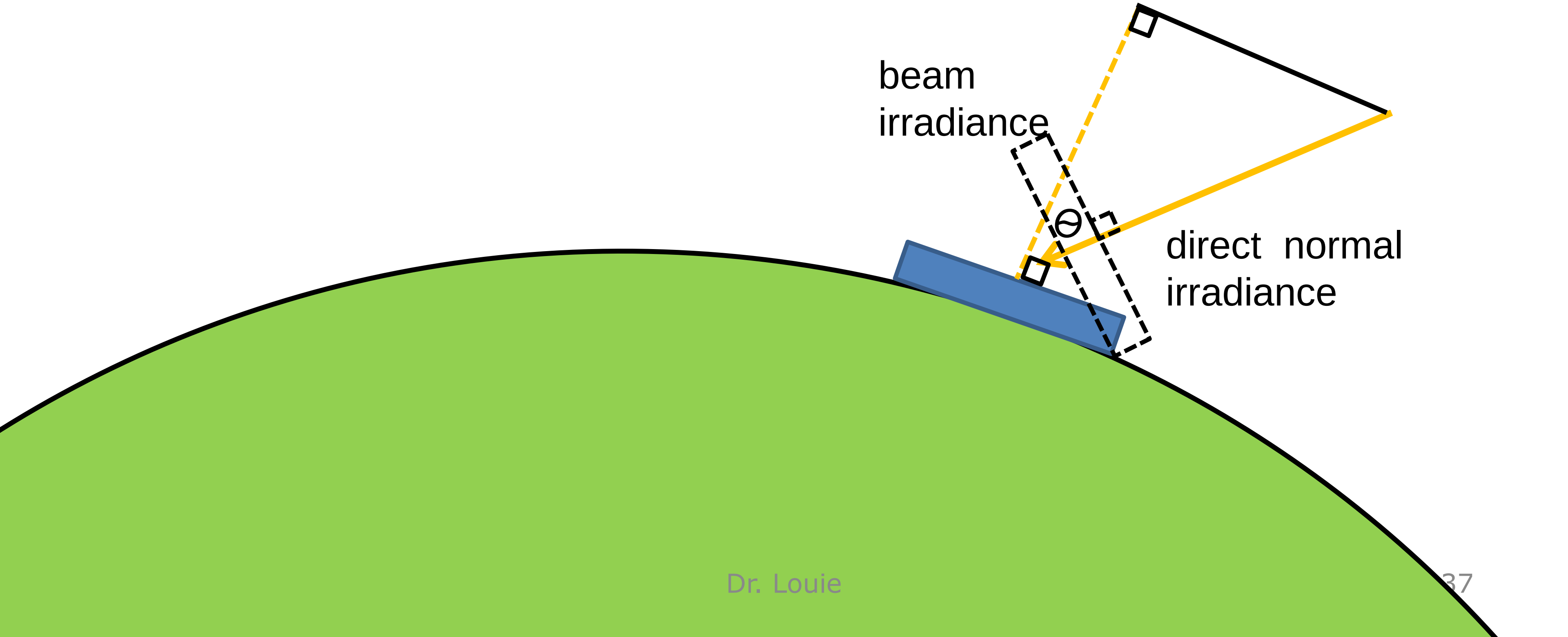
Solar Irradiance

Direct Normal Irradiance: beam irradiance on a surface that is normal to the beam

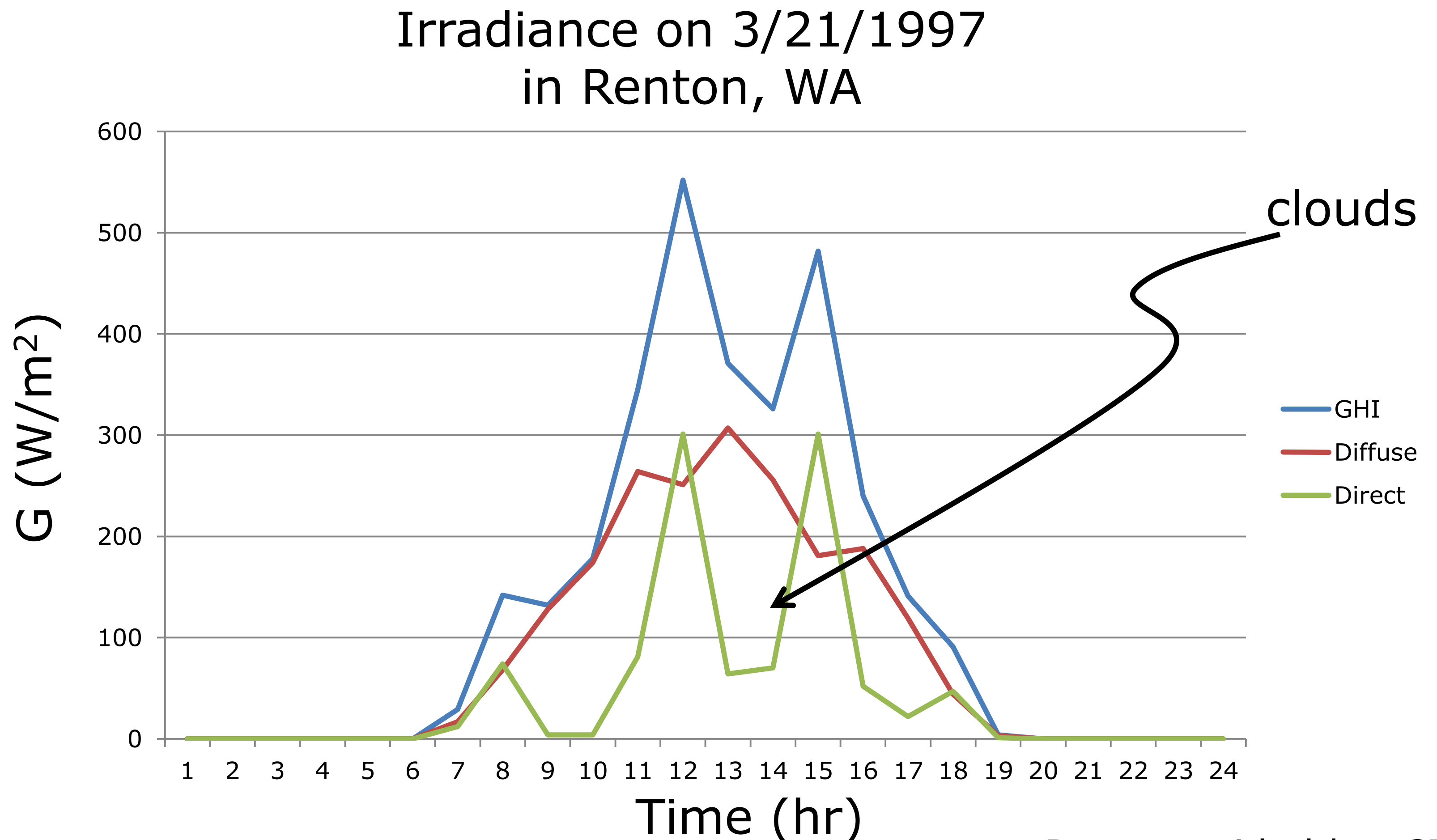


Solar Irradiance

- DNI is related to beam irradiance by:
  - $G_b = G_{DNI}\cos(\theta)$



Solar Irradiance



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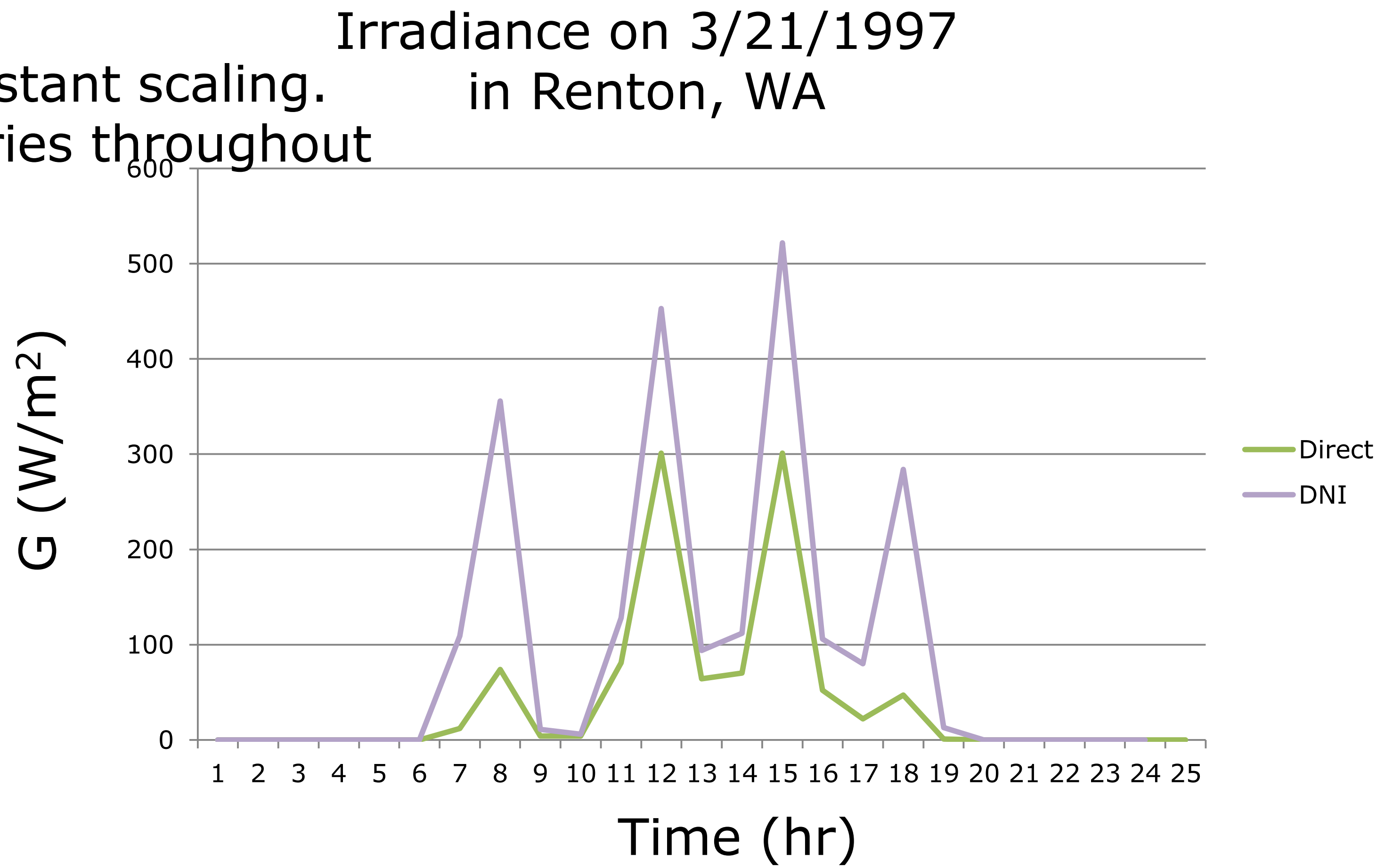
Solar Irradiance

Not a constant scaling. $\cos(\theta)$ varies throughout the day



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Solar Irradiance

- For a given surface
  - $G_{GHI} = 240\ W/m^2$
  - $G_d = 188\ W/m^2$

- What is G_b?

Solar Irradiance

- For a given surface
  - $G_{GHI} = 240\ W/m^2$
  - $G_d = 188\ W/m^2$

- What is G_b?
  - $G_b = G_{GHI} - G_d = 52\ W/m^2$

Solar Irradiance

- GHI will always be greater than or equal to DNI
  - True
  - False

- GHI will always be less than or equal to DNI
  - True
  - False

Solar Irradiance

- GHI will always be greater than or equal to DNI
  - True
  - False
    - On clear days and with certain angles of incidence, DNI > GHI
- GHI will always be less than or equal to DNI
  - True
  - False
    - On cloudy days and with certain angles of incidence, GHI > DNI